

In-Medium Quarkonia at SPS, RHIC and LHC

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Abstract

A kinetic-rate equation approach in a thermally expanding medium is employed to calculate the evolution of charmonium and bottomonium distributions in heavy-ion collisions. The equilibrium properties of the quarkonia are taken from in-medium spectral functions which are schematically constrained by euclidean correlators from lattice QCD. The initial conditions for the rate equation (heavy-flavor cross sections, nuclear absorption) and the thermal evolution are constrained by data as available. After fixing two free parameters to describe charmonium data at SPS and RHIC, the predictions for LHC are discussed in light of recent data.

1. Introduction

Heavy quarkonia are an excellent tool to study the modifications of the basic QCD force in hot/dense matter. In vacuum, potential models provide a theoretically controlled and phenomenologically successful spectroscopy, serving as a calibrated starting point to utilize quarkonium properties in medium as a probe [1, 2, 3, 4]. However, the realization of such a program in ultra-relativistic heavy-ion collisions (URHICs) is a non-trivial task. The interplay of color screening and dissociation reactions in a locally equilibrated, yet evolving medium, as well as off-equilibrium aspects in initial conditions and in heavy-quark (HQ) kinetics, result in a rather complex problem. A viable theoretical framework to properly interpret experimental data must therefore be able to account for these aspects, while maintaining the connection to theoretically calculated in-medium properties. In particular, it should be able to encompass both charmonium and bottomonium observables, and a large range in collision energies, as are now available.

In Sec. 2 we recall our kinetic-rate equation approach to quarkonia in URHICs [5, 6], its inputs and parameters. In Sec. 3 we discuss applications to charmonium (3.1) and bottomonium (3.2) data, mostly comparing predictions to recent LHC data. A short summary is given in Sec. 4.

2. Kinetic Rate Equation

Starting from the Boltzmann equation one can integrate out the space and 3-momentum dependencies to obtain a rate equation for the quarkonium number, N_Q ,

$$\frac{dN_Q}{d\tau} = -\Gamma_Q (N_Q - N_Q^{\text{eq}}), \quad (1)$$

where $Q = \psi, \Upsilon$. This form renders the relation to the “transport” parameters particularly transparent. The equilibrium abundance, N_Q^{eq} , depends on the quarkonium mass, m_Q and binding

energy, ε_B^Q , as well as on the HQ mass, m_Q , via relative chemical equilibrium at fixed HQ number. The temperature dependence of these quantities is taken from a T -matrix approach [7]. In addition, N_Q^{eq} is corrected for off-equilibrium HQ distributions (which suppress the formation rate) using a relaxation-time approximation (which has been verified to work well [8]). The pertinent τ_Q^{eq} is one of the parameters of the approach. The type of the inelastic reaction rate, Γ_Q , depends on the relation of ε_B^Q to T . For $\varepsilon_B^Q < T$, quasifree dissociation prevails (Landau damping of the exchanged gluon), while for larger T gluo-dissociation (singlet-to-octet transitions) takes over. We adopt the former (latter) for charmonia (bottomonia), where the precise value of the coupling constant is utilized as a second fit parameter. The resulting charmonium [6] and bottomonium [9] spectral functions are checked against euclidean correlators from lattice QCD. The initial conditions of the rate equation consist of the numbers of (would-be formed) quarkonia and heavy quarks, corrected for “cold-nuclear-matter” effects (shadowing, Cronin effect and nuclear absorption). They are determined from available experimental cross sections or interpolations thereof. The evolving medium is modeled by an expanding thermal fireball constrained by hadro-chemistry, hadron yields and spectra. The quarkonium ground and excited states are evolved with their individual binding energies and reaction rates, to account for feeddown.

3. Quarkonium Phenomenology in URHICs

The simultaneous study of charmonium and bottomonium observables in URHICs is particularly valuable, since the differences in charmonium and bottomonium binding (aka screening effects), as well as in open-charm and open-bottom content (aka reaction rates) enable a much improved discrimination power of bound-state suppression and regeneration mechanisms.

3.1. Charmonium

In Ref. [6] we have employed the above-described framework to conduct a systematic analysis of J/ψ data in Pb-Pb and Au-Au collisions at top SPS ($\sqrt{s}=17.3$ AGeV) and RHIC ($\sqrt{s}=200$ AGeV) energies, respectively. We have investigated both a strong- and a weak-binding scenario, where the former describes the data slightly better and gives values for our two parameters consistent with the T -matrix approach [7], i.e., $\alpha_s \simeq 0.3$ in the quasifree dissociation rate and $\tau_c^{\text{eq}} \simeq 5$ fm/c for the kinetic charm-quark relaxation time. We will therefore focus on this scenario from here on. Predictions have then been made for LHC and lower RHIC energies. For the latter, the centrality dependence of the total nuclear modification factor, $R_{AA}(N_{\text{part}})$, has little \sqrt{s} dependence, consistent with recent PHENIX data [10]. However, the composition of the J/ψ gradually changes with an increase in both the suppression of the primordial component and the regeneration, reaching ca. 30% of the total in central Au-Au.

The “degeneracy” in the SPS/RHIC regime was predicted to be broken at the LHC [11], due to the increase in charm cross section which enhances regeneration more than primordial suppression. The agreement with recent ALICE dimuon data (at somewhat forward rapidity) is fair, cf. Fig. 1. In particular, the tell-tale signature of the regeneration component at low transverse momentum is confirmed. Very similar results are obtained in the transport approach of Ref. [13], which differs in details of the implementation, but overall asserts the robustness of the conclusions. The statistical hadronization model also accounts for the centrality dependence of the J/ψ yield [14], using somewhat smaller charm cross sections than used in the transport models. This is due to the off-equilibrium effects in the latter.

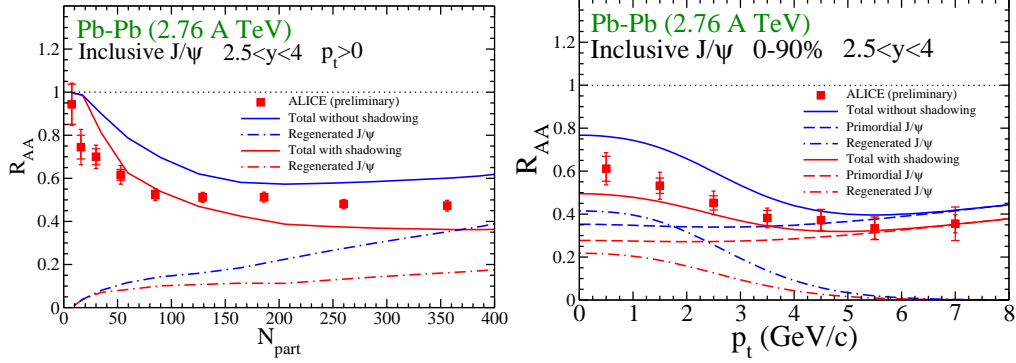


Figure 1: Predictions of the kinetic-rate equation approach [11] for the inclusive J/ψ nuclear modification factor in Pb-Pb(2.76 ATeV) as a function of centrality (left) and transverse momentum (right), compared to ALICE data [12]. Blue and red lines correspond to a charm cross section (per unit rapidity) of 0.5 mb and 0.33 mb, respectively.

Another signature of regenerated charmonia is the collectivity that they inherit from the charm quarks, which is much larger than from path-length type suppression effects. However, as is well known, a large radial flow suppresses the v_2 of heavy particles at low p_t , which is unfortunately where the regeneration contributes most. Nevertheless, first LHC data show a promising signal (Fig. 2 left) while at RHIC the current data accuracy does not permit a definite conclusion yet (Fig. 2 right).

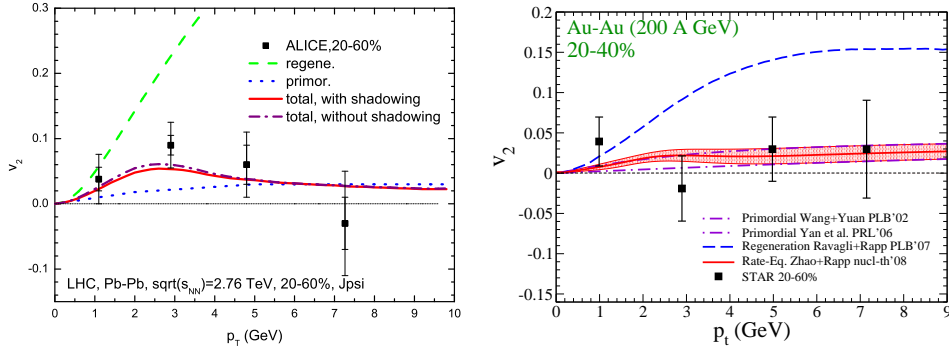


Figure 2: Elliptic flow of inclusive J/ψ in semicentral Pb-Pb(2.76 ATeV) (left) [15] and Au-Au(0.2 ATeV) (right), compared to ALICE [12] and STAR [16] data, respectively.

3.2. Bottomonium

Utilizing the rate-equation approach for bottomonium production, their degree of suppression has been identified as a rather sensitive measure of color screening, in connection with appropriate dissociation reactions [17]. This has recently been revisited using updated input for open-bottom and bottomonium cross sections at 2.76 TeV [9]. Indeed, the resulting $\Upsilon(1S)$ R_{AA} agrees reasonably well with CMS data in the strong-binding scenario (Fig. 3), but is suppressed too much in the weak-binding scenario. On the other hand, $\Upsilon(2S)$ is strongly suppressed even in the former (Fig. 3 right), with the finally observed yield ascribed to regeneration. This should be tested in the p_t spectra.

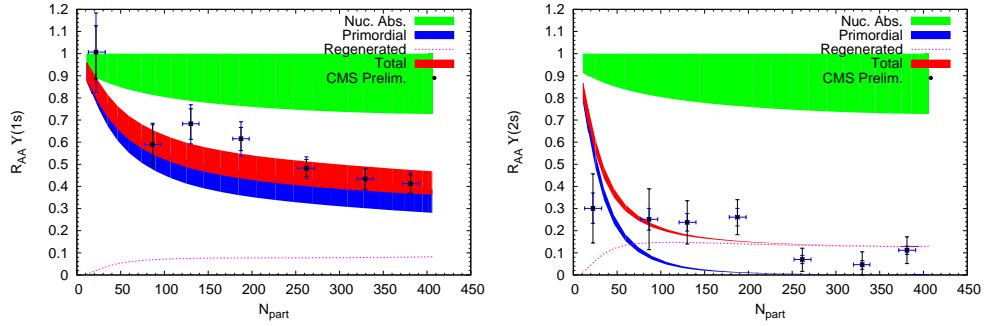


Figure 3: Centrality dependence of nuclear modification factors for inclusive $\Upsilon(1S)$ (left) and $\Upsilon(2S)$ (right) [9], compared to CMS data [18].

4. Summary

A kinetic-rate equation approach, implementing in-medium quarkonium properties into a thermal bulk-evolution model, is found to provide a suitable tool (with predictive power) to interpret J/ψ and Υ observables in URHICs. In particular, a gradual increase of regeneration contributions to J/ψ production from SPS via RHIC to LHC is supported by recent LHC data, showing an increase in R_{AA} . The associated low- p_t enhancement and v_2 signal corroborate this interpretation. Bottomonium observables, while possibly not free of regeneration, give a more direct access to the in-medium QCD force; the moderate suppression of $\Upsilon(1S)$ at LHC (and RHIC) suggests that a strong binding potential persists into the QGP, which may well be related to a small HQ diffusion coefficient. Systematic improvements of the approach are in progress.

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